Development of Storm Surge Barriers for the New York Metropolitan Area

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ABSTRACT

At the invitation of the ASCE Met Section Infrastructure Group, CH2M HILL presented a concept for a storm surge barrier at a seminar entitled, "Against the Deluge: Storm Surge Barriers to Protect New York City," held on March 30th and 31st 2009 at the Polytechnic Institute of NYU. That barrier, the "Outer Harbor Gateway," was one of four barriers presented at the seminar (Bowman et al. 2009).

Since Hurricane Sandy struck the region on October 29th and 30th 2012, bringing record storm surges and damage to New York, New Jersey and Connecticut, there has been an increased level of interest in storm surge barriers. This paper summarizes many of the questions that have arisen related to barriers such as the Outer Harbor Gateway and the possibility of storm surge barriers protecting the areas of New York and New Jersey that flooded as a result of storm surge in the harbor. A number of issues are discussed and topics for future study are suggested as the region assesses an array of options for minimizing the impact of future storm events.

BACKGROUND

Papers describing concepts for four barriers were presented at the 2009 seminar, as shown in Figure 1:

- A 100 ft wide Arthur Kill barrier between New Jersey and Staten Island, NY with 6 floating control gates, with integrated tidal power generators, and two locks, the larger of which can accommodate a 140 ft wide vessel. The barrier height is 28 ft above water level and the water depth is 40 ft at mean low water;
- The Verrazano Narrows Barrier between Brooklyn and Staten Island, comprising 16 lifting gates, 130 ft wide with restricted headroom; 2 lifting gates, 165 ft wide with an air draft of 85 ft; and one pair of sector gates with a total span of 870 ft and unlimited air draft. The barrier height is 30 ft above water level and the water depth is 100 ft;
- The East River Barrier in Long Island Sound, between the Bronx and Queens, is formed by a series of 100 ft wide, bottom hinged flap gates, raised by hydraulic cylinders under the flaps, set in 40 ft of water. The gate is folded flat on the river bed when open, allowing vessel traffic to sail over it. The concept suggests that the cylinders might be accessible using seals around the perimeter of each gate to allow dewatering below the flaps;
- The Outer Harbor Gateway across the harbor entrance from Sandy Hook in New Jersey to the Rockaway Peninsula in New York, comprising a 5 mile long causeway, 30 ft above water level and in water that is generally 20 to 30 ft deep, and 50 ft deep in the main shipping channel. The barrier has 2 pairs of large radius sector gates, each for a 600 ft clear channel, a 300 ft lifting gate with unlimited air draft, a smaller navigation opening for local vessels, and provisionally 50 sluices gates, each 80 ft wide. The causeway is extended to high ground by 13 miles of berms.

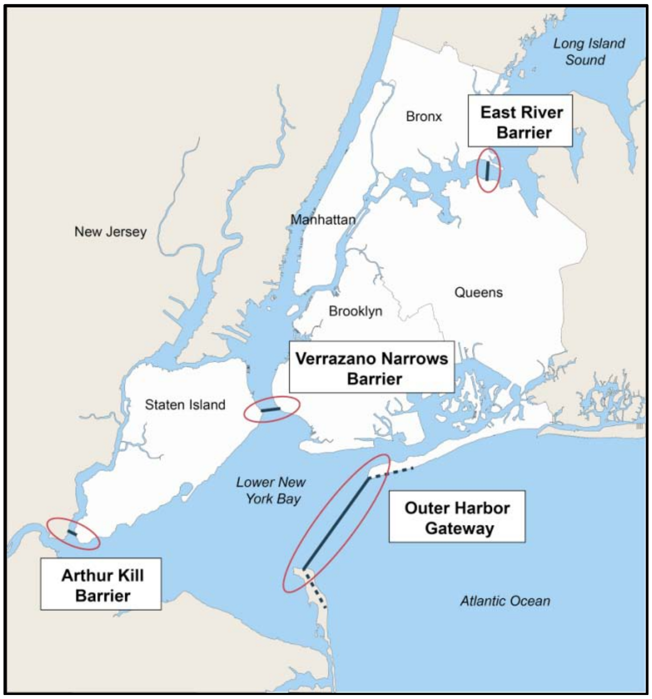

Figure 1 – 2009 ASCE Seminar barrier locations

The first three of the barriers listed above could be used together as a coordinated defense to close off the three main waterways to prevent a surge from entering the inner harbor. It appears that the Outer Harbor Gateway, which would prevent the storm surge from entering the Lower Bay, would replace the functions of both the Arthur Kill and the Narrows barriers. Therefore, if it were used in conjunction with the East River Barrier, this two barrier system would replace the three barrier system. A detailed study of the options for entire systems would be needed to verify the exact number and placement of the barriers.

The Outer Gateway Barrier concept, shown in plan in Figure 2, drew heavily upon a barrier that is now operating successfully at St. Petersburg in the Russian Federation. That barrier, designed by Halcrow (since acquired by CH2M HILL), was closed for 12 hours on December 26, 2102, and again the following day, to prevent a storm surge flood. Had the barrier not been in place, this would have been the fourth highest flood in the recorded history of the city. As it was, the population was largely unaware that a flood event had occurred.

While the Outer Harbor Gateway concept was based on the successful St. Petersburg barrier, there are a number of issues that would need to be addressed in further depth to validate assumptions and to develop the concept further.

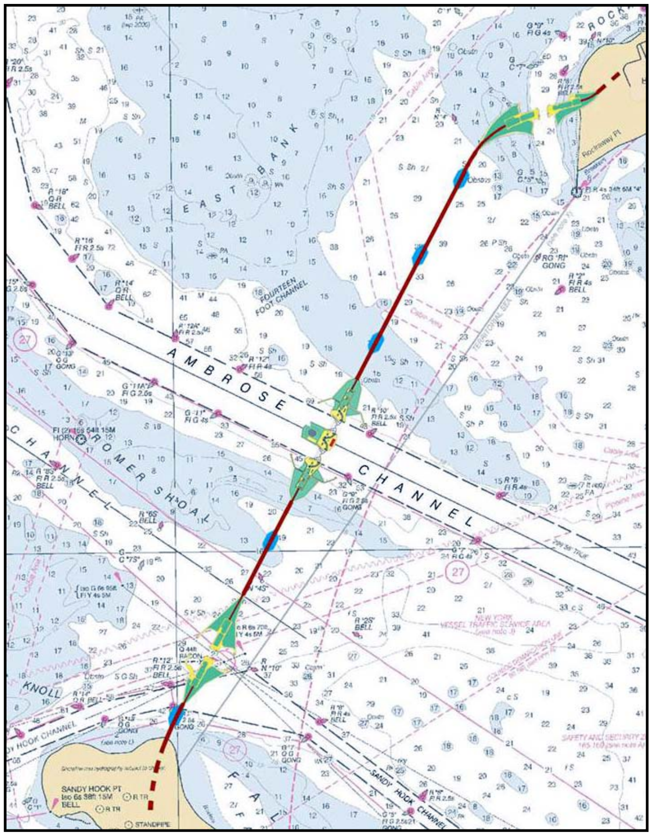

Figure 2 – Layout of Outer Harbor Gateway

This paper revisits some of the critical design and construction considerations, highlighting decisions that will impact the final design, and discusses issues to be addressed as the design of a barrier advances.

The paper concludes with a discussion of issues that have been raised in the public discourse related to the cost, appearance, efficacy, and timing of the barrier construction. Other barrier concepts, including those presented at the 2009 seminar, would have similar issues and concerns and would follow a similar development process.

The paper does not discuss the relative merits of various strategies for mitigating damage from storm surges or make any predictions of the likelihood of future events. Its intent is to discuss a potential design for storm surge barriers, and to describe the way forward in the design process.

KEY DECISION POINTS

As part of advancing the storm surge barrier concept, a number of key criteria must be established and addressed, as discussed below.

Functional Requirements - At its simplest, a marine or maritime barrier consists of two principal parts: movable gates and the supporting, static substructure. There are two primary functional requirements for any system of gates as described below.

First, the gates must open and close on demand with a high degree of reliability. The demand is the surge flood, which cannot be scheduled other than having some months, the "surge flood season," identified as potentially more vulnerable to storm surges than others. The reliability comes down to invoking confidence that the system will operate as designed. This is primarily related to the reliability and redundancy of mechanical and control systems.

Second, the gates must be strong enough to withstand the design load specified. By extension, the static substructure must also be strong enough to withstand the design load specified. The definition of withstand should also be considered. It is taken to mean that the gate and the substructure must be able to perform their functions in resisting the storm surge without incurring damages that would prevent them from resisting further storm surges effectively without major repairs.

Design life - A fundamental factor at the beginning of any design process is to specify the design life of the structure and its principal components. This is a first step in the development of a number of critical design parameters. The overall life of the barrier may be greater than that of its components, since it can be assumed that replacement of components is a planned activity - from relatively small items such as hydraulic pumps to large, very costly components such as gates.

Water Levels and Surge Heights - Papers presented by Bowman and Bowman and by Emanuel and Ravela (ASCE 2009) indicated that water levels are forecast to rise and that severe hurricanes are forecast to become more frequent and more intense. Since the threat of storm surge flooding will increase with time, the design life is a fundamental factor in determining the height of the structure required to provide the defense.

As part of any barrier design, detailed modeling will be required to predict future storm surge heights. As part of the modeling effort, a consensus must be reached on the rate of assumed sea level rise over the design life of the structure. As an example of the interplay between design life and barrier height, CH2M HILL is currently studying the possibility of increasing the height of the Thames River Barrier system in London given the anticipated rise in sea level beyond its original design life.

Cost Variables - As with any major infrastructure project, the engineering team must consider initial construction costs and anticipated maintenance costs over the design life of the structure in order to minimize the total lifetime costs. The water level and the potential storm surge height during the design life must be forecast in order to define the barrier's height.

As an example, the height of the Outer Harbor Gateway concept design that was proposed at the 2009 seminar was 30 ft. This was based on a specified storm surge of 20 ft occurring on top of a 3 ft tide, plus a 5 ft wave and a 2 ft freeboard (height of the barrier above the surge). The budget cost estimate presented indicated a capital cost of $5.9 billion. Variations in overall height would have significant effects on the amount of materials required and therefore the cost. A rough calculation indicates that a 5 ft reduction in height would save some 10% of the volume of causeway and berm materials, allowing savings in the overall capital costs.

Maintainability – Maintenance of the gates must not cause significant disruption to vessel traffic. The Outer Harbor Gateway concept adopted large radius sector gates, which are normally completely out of the water and operated by land-based equipment, in large part because other gates would normally be in a submerged position and driven by submerged or partially submerged machinery. It was concluded that, over the lifetime of the structure, other gate types would require a higher maintenance budget while potentially providing lower reliability.

Similarly, the barrier structure relies largely on a conventional revetment structure using rock or concrete armor units based on the initial cost and durability of this type of construction (compared to submerged steel structures), its ability to adjust to settlement, and the relative ease of repair.

Need for Gates and Sluices - Any barrier will impinge on the existing flows in the waterway that it closes off. This could have negative effects on a number of important factors, such as environmental and ecological considerations, silting, scour and deposition, water quality and industries such as fishing. Therefore, engineered measures will be required to allow as much water as possible to pass through the barrier when it is in its normal, open position.

Water Depth and Currents - Marine construction is difficult and costly, and that difficulty increases with the depth and speed of the water. Issues include keeping working vessels on station and the accurate placement of components at depth.

Another consideration for the operating barrier is the large volume of free flowing water that will now be diverted through the channel opening. Where large volumes of water are redirected, there will be very swift operating currents, increasing the difficulty of navigation. The problem will be greatest in areas of deep water and high current flows, such as at the Verrazano Narrows in 100 ft of water, and will be less pronounced at the Outer Harbor Gateway where water depths are 20 ft to 30 ft and currents are much weaker.

Geotechnical Issues - Based on knowledge of the local geology and on publically-available data, the characteristics of the soils beneath the proposed Outer Harbor Gateway appear to be well suited to supporting the revetment structure with little or no modifications or support structures. This is discussed in more detail later in the paper.

ISSUES TO BE ADDRESSED GOING FORWARD

The Outer Harbor Gateway concept was developed from the 15 mile long St. Petersburg barrier. While the in-water portion of the Outer Harbor Gateway would be only 5 miles long, it is in a similar water depth and protects a city that is situated in a similar relationship to a bay open to the ocean and at a similar elevation relative to normal water levels. The discussion below centers primarily on adapting the St. Petersburg concepts to the Outer Harbor Gateway, but many of the issues would apply to any barrier designed for the harbor.

How the Outer Harbor Barrier works - In general terms, a storm surge barrier works like a dam that is only deployed when a storm surge raises the water elevation in open water (in this case, the Atlantic Ocean) to levels that would flood low-lying land (areas of New Jersey and New York) surrounding a harbor. In a more specific sense, the Outer Harbor Gateway works by closing a series of gates, for both navigation channels and sluices, to limit water flowing through the barrier from the higher water levels outside the barrier.

The Outer Harbor Gateway gates would not provide a watertight barrier. Given the scale of the gates and the nature of the supporting substructures, it would be quite possible for settlement to occur that could significantly affect tolerances and clearances. Tight tolerances in these circumstances would be difficult to construct and expensive to maintain, and could lead to damage to the gates or substructure where displacements occur. It is quite acceptable for a limited amount of water to be allowed to flow past and under the gates, such that the gates impede the surge rather than stop it completely. This is the principle successfully adopted for the St. Petersburg Flood Defense Barrier and the Thames Barrier.

A feature of the Outer Harbor Gateway is the creation of flanking embankments extending onto land on both sides of the in-water barrier, into Sandy Hook and into the Rockaways. The purpose of these raised terrain enhancements (or berms) is to provide storm surge protection to the upland areas. The embankments would have a top elevation approximately 30 ft above sea level, which is consistent with the main length of the in-water causeway across the bay in the concept design.

The Need for a Single Controlling Entity - The paper by Roth (ASCE 2009) described a lesson learned from the Hurricane Katrina flooding of New Orleans in 2005. It was recorded that the city's defense was fragmented by different areas and levels of authority and responsibility, funding that did not match technical need or understanding, different geographical areas such as levee boards that did not adopt common strategies or have a common understanding of where their geographic responsibilities ended, defense structures with different design criteria and levels of reliability and, in some cases, an understanding of the capability of defenses that was shown to be overly optimistic. In short, there was no coherent or consistent strategy for defense.

It seems that the defense for a major metropolitan area with a number of interrelated agencies, departments and interests, which straddles two states, would be well served by an integrated operational management system. Such a system would allow the setting of high level aims and targets within an overarching plan, with clear and auditable delegation of authority and responsibility, and a cascade of integrated functional requirements and level of design capability from the overarching plan through appropriate levels down to the local components. The system would also provide schedule and budget control and targets.

The deliverable of such an integrated operational management system would be a set of systemic procedures and protocols to forecast the threat of storm surge, prepare the barrier and other defenses, and then deploy the defenses to meet the threat. This would take the form of a "Decision Support System."

It is anticipated that a comprehensive forecasting system would be established and, married to a hydraulic model of the New York bight, the bay, and the river, it would determine the time to close and open the gates. This would be based on forecasting when water levels in the harbor would reach the recognized flood defense level, taking into account joint probabilities of contributing data such as fluvial flow from the rivers that could fill the harbor from the inside. It will be a goal to keep the barrier closed for as short a time as possible. The balance to this is the fact that, subject to the final approval from the city or state's emergency authorities, operating the gates during the surge cannot be subject to approvals from various agencies. In St. Petersburg, a system process was developed and commissioned by which all parties (such as the port, the city, and transportation authorities) were advised at various stages once a flood was forecast. The system currently looks 48 hours ahead, but there are plans to extend this to 60 hours.

This methodology assumes that other parties apart from the barrier operator have no say in whether or not, and when, the barrier is closed. Although this approach has been accepted for St. Petersburg, alternative scenarios could be developed for New York.

How is the Decision to Close the Barrier Made? - The overall decision by the barrier operator of when and how to close the barrier would be based on an analysis of myriad information including storm surge height, wind speeds, storm radius, speed of translation (speed over the ground), forecast arrival in the area of interest, prediction of fluvial flows and joint probability assessments. This is likely to be made available to the decision makers using a computerized management and information matrix system, using the logic defined in the Decision Support System, allowing a consistent presentation of appropriate information at different steps in the process, along with templates for information to be issued to stakeholders along with more customized information. The timing of the opening of the barrier may be just as important as the timing of its closure. The final decision to open or close would be the outcome of a set of steps and procedures laid out in the Decision Support System. Affected stakeholders, such as vessels at sea that are seeking to make port, must be considered and advised of their options.

Taking a large barrier such as the Outer Harbor Gateway concept as an example, this formalized process is likely to include the following elements:

- Forecasting weather using meteorology and hurricane forecasting tools to provide a forward projection of expected weather conditions
- Monitoring stations that measure the actual conditions and are used to validate the forecast model
- A decision process that uses forecasts of the storm surge and performs an automated assessment of the risk to the metropolitan area which can then be used by the barrier operators to inform their decisions. This assessment will be repeated as a hurricane approaches the area of interest, with increasing threat levels being monitored and eventually informing a decision that

starts the activation of the barrier defense, as described below.

- The decision process instigates preparatory actions. An alert status is issued to all relevant stakeholders.
- Preparing a schedule and timing to call in staff required to initially prepare the gate systems for deployment, close the gates, open the gates and place the gate systems back into a state of readiness, depending on the forecast need for their next use. It is assumed that specifically trained staff are required but that not all are employed full time at the barrier; a dedicated core team would coordinate and lead the required work.
- Pressurizing and testing the hydraulic systems, flooding the dry docks and opening the dry dock closure gates.
- Deploying the defense gates to meet the schedule defined by the Decision Support System. This includes decisions on when to open gates, which ones and in what order.
- Opening the gates after the storm surge has occurred, in accordance with the schedule defined by the Decision Support System.
- Closing the dry dock closure gates
- Pumping out dry docks and landing the gates on blocks
- Checking all gates for damage

Timescale for Deployment and Recovery - The gates of the St. Petersburg barrier, which is taken as a practical template for the Outer Harbor Gateway concept design, are used to demonstrate the types of operations that would be expected. The main gates, 450 ft long and 80 ft high with a radius of about 450 ft, are floated out from the permanent dry dock (assuming it is already flooded and the outer gates are open) and driven into position in 45 minutes by mechanical systems mounted on the barrier's concrete substructure. Figure 3 shows the St. Petersburg gates being floated to their deployed position. The St. Petersburg barrier uses a locomotive connected to the gate by a pin-ended strut while the similar Maeslant barrier in Rotterdam uses a rack and pinion drive to provide the gate movement. Studies would be required to identify the most reliable drive systems such that single mode failure would not render the barrier ineffective. This could mean spatial separation and redundancy in power systems, availability of tugs to pull the gates open or shut, and back-up air compressors or pumps to control water ballast.

Figure 3 – Large radius sector gate being floated into place

It then takes a period of some 20 minutes to flood special internal compartments in the gates and ballast them down into their defense position as shown in Figure 4. At this point, the gates do not physically touch in the middle and the gate bottoms do not seal onto the concrete floor of the channel – for the St. Petersburg gates, there is a gap of about five feet between the gate ends and a gap of about one foot under the gates.

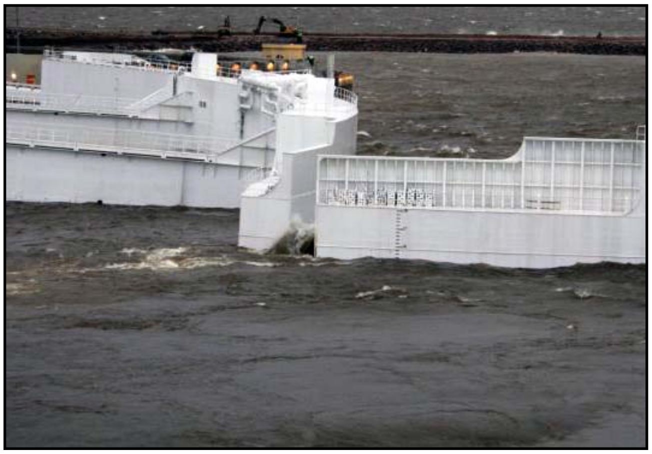

Figure 4 – Large radius sector gate ballasted down with gap between gate faces

Following the flooding, the ballast water in the internal compartments of the gates is removed by pumping or draining, which will take about 30 minutes, and the gates are driven back into the dry docks in about 45 minutes.

The 360 ft wide steel lifting gate on the secondary navigation channel (in the case of the Outer Harbor Gateway, at the Sandy Hook channel) can be raised from its parked position in the chamber in the sea bed into its defense position in about 30 minutes and lowered back into its parked position, also in about 30 minutes. The gate movement is purely vertical and uses four large hydraulic cylinders, one at each corner. The lifting gate at St. Petersburg is shown below in Figure 5.

Figure 5 – Lifting arrangement for vertical lift gate

Each 80 ft wide sluice gate can be lowered into position in 10 minutes, which is accomplished in groups of several gates at a time, making the total time to close all the gates at each sluice structure about 50 minutes. Raising each gate takes about the same time, but as this is done one gate at a time, the total time taken to fully open each sluice structure is about 2 hours. The gates are tainter in form and are raised and lowered by hydraulic cylinders, rotating about a pair of trunnion bearings.

Figure 6 – St. Petersburg Barrier sluice gates

Each of the times quoted above is dependent on the system being in a well maintained condition and adequate preparations having been taken in good time. Figure 6 shows a bank of sluice gates in the St. Petersburg barrier.

Location and Planning - Each of the barriers described in the various papers presented in the 2009 seminar was located based on common sense, some geotechnical information where available and an assessment of practicalities. A future design would require a holistic assessment as part of a detailed study, which would consider the hydrodynamics of the entire harbor, design issues, shipping navigation criteria, constructability and maintainability, flooding patterns, sewerage systems, housing and social developments, transport linkages and other infrastructure requirements throughout the local and wider areas.

There are additional concerns that the barriers, which are designed to protect areas within harbors, might actually exacerbate conditions outside of the barriers. This possibility was discussed in two separate papers in the 2009 seminar. In the paper by Kim, George and Simmons (ASCE 2009), water elevation increases were predicted to be approximately 0.2m (approximately 8 in.) at Sandy Hook and up to 0.14m (approximately 5.5 in.) at Willets Point. A paper by Bowman and Bowman (ASCE 2009) predicted ocean-side water level increases of up to 0.08m (approximately 3 in.). Both papers considered a system of three barriers, but neither considered the Outer Harbor Gateway.

An investigation of the water level variations induced by the Outer Harbor Gateway would require a large scale hydrodynamic model that considers all of the barriers and a range of meteorological conditions. It is expected that, since the Outer Harbor Gateway is adjacent to the ocean, the water level variations immediately beyond it would be less than for the other barriers which are in confined waterways.

Embankment Construction - Water depth has a tremendous impact on construction feasibility and cost. Although the Outer Harbor Gateway is approximately 5 miles long, it is in relatively shallow water. The nautical charts show that water depths along the proposed alignment average approximately 20 ft outside of the navigation channels (NOAA Chart 12327). Assuming a 36 ft-wide crest and 1 on 3 side slopes, the volume of the in-water barrier would be approximately 9 million cubic yards. The actual quantity will vary as the design is developed and actual dimensions and features – such as the plan geometry and tunnels within the revetment - are defined.

Construction of the causeway and the landside berms is well understood conventional civil engineering. As with the construction of most large revetments, construction would involve a combination of placing material from barges and dumping material from dump trucks ahead of the constructed portion of the revetment.

The relatively shallow water depths greatly simplify the construction operations and limit the material required for the embankment. In addition, there are very low currents along the alignment, especially compared to the currents in the waterways within the harbor (and particularly at the Verrazano Narrows). This shallow, relatively low energy working environment facilitates the operation of marine construction equipment and the accurate placement of underwater materials. In addition, the shallower and lower energy the working environment, the safer that construction tasks are likely to be, particularly in cases where diver operations are necessary.

Sourcing Materials - A large quantity of rock will be required for the construction of the causeway and berms, and sources would need to be identified as part of any feasibility studies. The northeastern US has many quarries with high quality rock. In selecting rock sources, factors to be considered include quality and gradation of rock, distance from the site, and distance from the source to a navigable waterway – since transportation of these very large quantities by barge will be more economical and less disruptive than delivery over the road. Studies would determine an optimum source or sources of materials involving materials technology, economics and logistics.

Sustainability – Any infrastructure project must consider sustainability during design as well as over the lifetime of the structure.

Construction of any barrier will be a massive effort and the plans and specifications must address how to minimize environmental impacts while the barrier is being built. Minimizing dredging will be a key element in minimizing disruption to marine life, and the required Environmental Impact Statement will emphasize this. In fact, the winning design-build bid (approved in December of 2012) for the replacement of the Tappan Zee Bridge between South Nyack and Tarrytown, NY over the Hudson River required the least dredging of the three submitted bids, and this was among the reasons cited for its selection (NY State Thruway Authority).

The sourcing of building materials, particularly rock for the 5-mile long embankment, will have a tremendous environmental impact. Given the very large volumes discussed above, it will be important that the rock is sourced as locally as possible and that it is quarried and transported in a way that minimizes the use of fossil fuels. This would suggest that the rock quarries should be located near the water and as close to the site as possible so that the rock can be transported to the construction site in large quantities in short trips by barge. This will also reduce transportation costs as discussed above.

The energy consumed on site and the resultant emissions will be considerable. A number of agencies, including the federal government, have developed sustainable guidelines for construction sites and equipment. The Port Authority of NY & NJ has developed "Sustainable Infrastructure Guidelines" with sections that address materials, construction, and maintenance and operation. The construction section specifically addresses green construction equipment and methods to minimize airborne pollutants generated by diesel-powered equipment. It is expected that these types of requirements would be mandated in the construction of any barrier.

Ship Navigation Requirements - Any barrier for the port of New York and New Jersey must be able to accommodate the substantial volume of shipping - estimated in 2010 as 67,000 commercial vessels per year per the Army Corps of Engineers Data Navigation Center - that enters or leaves New York without causing any (or at least no significant) delays. It is difficult to project how volume might change in the future. Even if cargo volumes were to increase, since larger ships will be using the newly deepened channels, vessel counts may not increase accordingly.

The width and depth of the barrier openings must be sufficient to accommodate vessels wider and deeper than those now sailing. The newest container ships such as the Maersk "Triple-E" vessels will be over 1,300 ft long with beams of 194 ft and drafts of 47.8 ft. With the expansion of the Panama Canal, and the soon-to-be completed NY/NJ Harbor Deepening Project (bringing the main channels to a 50 ft depth), vessels of this size or larger will be entering the port through the Ambrose Channel in the very near future. The ultimate size of the barrier openings would be developed in close consultation with the authorities responsible for the regulation and authorization of vessel traffic.

Figure 7 – Plan on Ambrose Channel crossing barrier

The gate arrangement shown in Figure 7 above was developed for the barrier where it closes off the main navigation channel, the Ambrose Channel. It uses a twin gate arrangement to facilitate separate channeling of in and out vessel traffic, allowing controlled and safe two-way flow of vessels without causing a bottleneck and impediment to the substantial traffic volume. However, modeling of the arrangement would be required to determine that the speed of vessels approaching and passing through the barrier navigation channels would be appropriate and safe under all conditions of tide and operational limits of weather. The arrangement would also require a set of navigation protocols to be developed and promulgated that clearly set out the necessary rules and regulations for mariners. This would be required for any gate system.

Ground Investigation Considerations - New York Harbor is located at the mouth of the Hudson River, and is relatively shallow and flat bottomed, with areas of sandy and mud bottom. It is divided into the Outer Harbor, the portion from the proposed Outer Harbor Gateway to the Verrazano Bridge, and the Inner Harbor, consisting of the portion from the Narrows, where the Verrazano Bridge spans, to the southern tip of Manhattan at the Battery. The ground conditions for the barrier concepts associated with a three barrier defense (for the Inner Harbor) have been described in some detail in the paper by Lacy, DeVito and De Nivo (ASCE 2009).

Water depths along the proposed Outer Harbor gateway vary up to about 30 ft, except at the dredged Ambrose Channel, where water depth ranges from 45 ft to 53 ft, and at the dredged Sandy Hook Channel, where water depths range from 35 ft to 40 ft (all water depths are relative to Mean Lower Low Water.

US Army Corps of Engineers subsurface information for the Ambrose Channel indicates that the area is generally underlain by Pleistocene deposits consisting mostly of sands and gravels, with minor amounts of silts and clays (USACE S-AM-3B). At the shallower depths, there are recent silt deposits at the seabed. However, the thicknesses of these surficial soils are fairly small, up to several feet at the most, and can be handled easily during construction. The underlying deposits are generally competent materials that are suitable for support of the pressures produced by the proposed barrier structure, and the anticipated settlements, which are mostly expected to be elastic settlements, are anticipated to be tolerable. Additionally, due to the flexible nature of the barrier, any unexpected deformations that result from settlement could be easily corrected by placement of additional rock.

While the barrier structure is primarily designed for coastal conditions, secondary design considerations must also be considered. Among these are geotechnical design considerations, which include the following:

- Design – The barrier geotechnical design will require consideration of the expected seepage within the structure, and its effects on slope stability. Also, seismic considerations need to be included, although these are not expected to control the design. Additionally, the pressure induced on the foundation soils by the barrier structure and the expected resulting settlements will require assessment.
- Stability - The barrier width needs to be sufficient to withstand any water seepage forces, and stability of the side slopes needs to be verified under the most severe design conditions.
- Foundations - Minimal recent silt deposits are expected along the proposed alignment of the barrier, although it is noted that minimal subsurface geotechnical data is currently available; significant additional information will be required.

Maintenance - The steel gate structures would require regular maintenance as would the protective coatings and the cathodic protection systems used to reduce corrosion. These activities would take place about every 20 years and would require the gate to be in a dry dock. In contrast, maintenance of the cylinder arrangement located underneath the East River flap gate (Abrahams, ASCE 2009) would be challenging if the gate were not removed. Gate structures could also require repair of damage caused by ship impact. For many gate types, this maintenance or repair would require the gate to be removed temporarily from its operational position, which would require special equipment or vessels, be a costly exercise and could disrupt normal navigation.

Similarly, maintenance on any supporting mechanical, electrical, instrumentation, control and automation (MEICA) systems could require normal operations to be suspended or even, in significant equipment cases, for the gates to be removed to allow the component to be refurbished or replaced.

Maintenance of the gates is, then, an important decision point and it is mentioned in each of the papers describing the four barrier concepts (ASCE 2009).

The advantage for the main gates of the Outer Harbor Gateway is that they are parked when open in permanent dry docks, as shown below in Figure 8. A set of gates at each dock entrance closes off the dry dock so that it can be pumped out for maintenance access to the structure and any supporting MEICA systems. This also allows entire gate structure to be inspected on a regular basis.

Figure 8 – St. Petersburg gate in drydock

The St. Petersburg lifting gate is shown in Figure 9 below. As with this gate, the Sandy Hook channel lifting gate would be maintained when the gate is lifted clear of the water level, as shown below, and hence does not need to be removed. Shipping would be disrupted, but the main navigation channel would always be available as an alternative route.

Figure 9 – St. Petersburg lifting gate in maintenance position

The sluices could be maintained in-situ by raising them into the sluice structures, as shown below in Figure 10 at St. Petersburg.

Figure 10 – St. Petersburg sluice gate inside housing

Maintenance of the MEICA components of the gates would take place at a greater frequency than the cycle of 20 years for the structure. Typically, hydraulic cylinders seals would be replaced every 10 years while the hydraulic oil would be replaced every 5 years, and so on, with annual, monthly and weekly cycles of component replacement and maintenance.

The concrete substructures are unlikely to require significant maintenance, but monitoring would be expected to take place on a regular basis. This would look at spalling, signs of corrosion of reinforcement, chloride penetration, and similar degradation. There should also be regular measurements of line and level to check for subsidence or other movement of the structure or the gate systems.

Ecological Impacts - The paper by Swanson, O'Connell and Wilson (ASCE 2009) discusses environmental, ecological and social impacts that could result from the installation of surge barriers. Without a great deal of study of a multi-barrier system, it is not possible to quantity the impacts. The paper addressed only three of the four barriers presented at the seminar; the Outer Gateway Barrier was not included. A summary of the environmental and ecological impacts discussed in the paper is provided below with commentary on potential mitigating measures.

<u>Altered Salinity Distribution</u> - The complex flows in the Hudson River are driven by inflows through Lower New York Bay and through Long Island Sound. The Hudson River is a highly-stratified estuary with relatively fresh river water flowing above the denser ocean water, creating a salt wedge of ocean water below. The location of the wedge varies with weather and tidal conditions. In the Hudson River, this wedge extends as far as 80 km north to West Point/Newburgh Swanson et. al).

The analysis reported by Swanson, O'Connell and Wilson (ASCE 2009) indicated that the physical barrier introduced by the Verrazano Narrows barrier is likely to provide an impediment at the bottom of the channel, since the channel is over 100 feet deep and a significant bottom sill, about 40 ft high, would be required beneath a 60 foot high gate. This would make the river fresher to the north as the barriers impede the flow of the deep salt wedge. While the impact of the altered wedge cannot be determined, it could disrupt spawning patterns and the distribution of many types of fish. The altering of the salt wedge, along with changes in sediment distribution discussed below, could have an effect on a new shellfish harvesting industry that is sensitive to the character of the bay bottom.

The Outer Harbor Gateway would not present as significant an impediment. Each of the navigation openings would have a concrete base which would be level with the channel bottom. Similarly, the bases of the sluices would be constructed flush with the surrounding seabed. However, studies would be required to assess the potential for altering the salinity of the bay, including consideration of sediment distribution which could build up shoals and subsurface banks that would disrupt the existing flows.

<u>Sediment Distribution</u> - Barriers alter the flow of water, increasing velocities through the gates and sluices. This will cause an overall change in the transport of sediment on both sides of the barrier, possibly resulting in a reduction in sediment transported from the ocean into the Upper Bay. This could reduce the need for navigational channel dredging while increasing the need for dredging near the barriers.

<u>Flushing</u> - It is likely that estuarine flow will be reduced and therefore will be less effective at carrying effluent that is discharged into the harbor estuary to the ocean. This is particularly important when untreated sewage is released from combined sewer outfalls and is not transported away from the harbor. The situation will be most severe during heavy rains when the barrier gates are closed and there is essentially no flow. Since the gates are typically opened and closed during the storm event (as tides ebb and flow), this situation could last for many hours.

A study would be needed to identify the locations where untreated sewage is discharged into the watercourses, the effectiveness of its mixing and dilution, and the duration for the chemical and biological processes to break the sewage components down to acceptable levels. The study would also consider the locations of barriers, the tidal and fluvial flows and mixing, and whether discharge into the larger expanse of the Lower Bay presents less of an environmental problem than discharge into the more confined Upper Bay.

Another consequence of the reduced flow would be the trapping of harbor debris which the Army Corps is tasked with removing. It is possible that the flows would be changed such that the debris accumulates at the barrier, simplifying the collection process.

Air Quality - There are direct and potentially indirect impacts on air quality from the construction of the Outer Harbor Gateway. There will be an increase in emissions from this major construction project using heavy equipment working for many years. In addition to the equipment working on site, there will be emissions associated with transporting large quantity of rock and/or concrete, perhaps over significant distances.

On the other hand, it would be possible to construct the barrier so that it supports a major roadway linking Sandy Hook to Breezy Point. Such a roadway would only be constructed if it were shown to improve traffic flows in the region. If this were the case, there would be a net reduction in vehicle miles traveled (and thus auto emissions) associated with cars that are currently not traveling efficiently on overburdened roads.

Dredging - The ecological impacts described above include an altered sediment distribution which will change the characteristics of material to be dredged as well as the overall quantities. The soon-to-be-completed Harbor Deepening Program will bring the main channels to a 50 ft depth. The Army Corps of Engineers projects that maintenance dredging needs between 2014 and 2017 will be approximately 750,000 cubic yards annually (ACOE, October 2012).

Studies using detailed computer models will be required to estimate changes in maintenance dredging volumes caused by the placement of barriers. The computer models will also predict how changes in hydraulic flows around the harbor will affect the distribution of deposition and scour. These models may also be augmented by a physical model of the entire harbor.

Since water velocities at the breakwater channels and sluices will increase over the existing velocities, sediment should not accumulate at these openings. It is likely, however, that sediment will accumulate in areas of lower velocity where there are no channel openings. Periodic dredging will probably be required in these areas, particularly if water depth is required for other uses such as tug and pilot boat mooring and staging or for marinas.

Landing the Causeway - Determining the location of the embankments on each shore would require a great deal of planning and community involvement to inform the engineering. On the Rockaway Peninsula, the relationship of the embankment to the Breezy Point neighborhood, which suffered a great deal of damage from the Sandy storm surge, would have to be considered carefully, taking into account its obstruction of the current views to the ocean. In addition, if the Outer Harbor Gateway and the embankments were to support a major roadway, the planning would have to consider the routing of the roadway in a way that minimizes disruption to the neighborhood while following a route that ties it into the existing roadway system in an effective and efficient manner.

The Sandy Hook lift gate, near shore, is shown in Figure 11 below. The Sandy Hook embankment would come ashore in the Gateway National Recreation Area, a National Park, surrounded by recreational beaches. A high embankment would change the character of the park and any design would be with the permission of and in close consultation with the National Park Service. As with the Rockaway Peninsula, if the embankment were to support a major roadway, the planning would have to consider the routing of the roadway in a way that minimizes disruption to the park while following a route that ties it into the existing roadway system.

Figure 11 – Rendering of Sandy Hook lift gate

Both embankments would have wide footprints that would occupy valuable upland. One option that might be considered would be to extend the current shorelines seaward using dredged material to compensate for this loss of upland by providing additional land for the embankments. In both cases, the embankments would have floodgates at regular intervals to allow pedestrian and/or vehicular traffic to cross through the barrier under normal conditions.

Multi-modal Transport Link - The concept for the Outer Harbor Gateway presented in 2009 allowed for a road access link to service the control building which it was assumed would be located between the main gates at the Ambrose Channel. It was also intended to provide maintenance access to the various structures and equipment located along the barrier's length.

The construction of a permanent causeway across the Lower Harbor offers the opportunity to invest in a multi-modal transport link which could provide a road system up to a six lane highway. The causeway also offers potential for a rail or light rail transit system. If the barrier were to become a major roadway, additional sources of revenue could be made available for its construction and, depending on the financing scenario, it could become a toll road producing revenues.

In addition, the barrier would offer the opportunity to provide recreational space along the causeway, and could allow the construction of a building for visitor center or other function. This destination could be linked by ferry to destinations in New Jersey and New York as well as tourist destinations such as Liberty Island, Ellis Island and Governor's Island.

Aesthetics - There is concern that a surge barrier would be visually intrusive. While this would be a very significant structure when viewed at a close distance, rising some 30 ft above MLLW, the bulk of the structure is below water level.

From a longer perspective, the in-water barrier and the onshore berm would change the landscape substantially, and it is inevitable that there will be considerable debate on whether this change is an acceptable trade-off for providing a defense against future flooding.

To better understand its likely visual impact, a three dimensional computer model would be very helpful. It would allow viewing of any proposed barrier from different viewpoints and angles, and would allow virtual fly-overs, drive-throughs, or transits of the structures. Figure 12 below shows an aerial view of the Outer Harbor Gateway from a three-dimensional computer rendering.

Figure 12 Aerial rendering of Outer Harbor Gateway with Sandy Hook lift gate in foreground

Regulatory Requirements - The US Army Corps of Engineers is federally legislated to regulate the balance of needs and advantages of any storm surge defense proposed in navigable waterways. It is constrained by three main statutory authorities: Section 10 of the Rivers and Harbor Act of 1899, which deals primarily with construction and dredging; Section 404 of the Clean Water Act, which deals with the discharge of dredged and fill materials; and Section 103 of the Ocean Dumping Act, which deals with the transport and discharge of dredged material. The paper by Scarano (ASCE 2009) indicates that storm surge barriers for New York would "present significant engineering challenges in their own right and would require the most rigorous, detailed regulatory examination." This examination would be initiated by an application for an individual permit, as normally required for complex projects and which requires the most coordination with and review by partner federal agencies, state and local governments, and other local stakeholders. This permit also requires public notification.

The review would be expected to address environmental, wildlife and historic properties as well as purely engineering issues and economic development. As such, it would be expected to include construction in navigable waterways and effects on water quality, aquatic habitat, endangered species, and financial or economic issues. The outcome of a regulatory review would be to grant or deny a permit, or to grant a permit with conditions.

Who Will be Protected? - Storm surge barriers can be designed to resist a specified storm surge in a specific location. Detailed computer models can explore different scenarios that vary multiple parameters such as wind speed and direction, amount of rainfall, and tidal levels, to predict conditions inside and outside of the barrier. GIS modeling, such as presented by Hill (ASCE 2009), can catalogue population and assets that would be in different zones and how susceptible individual areas would be to flood effects.

Storm barriers will protect areas within their confines; they will not provide protection to those outside the barriers. Any such protection must be provided by other means such as dunes or embankments that are beyond the scope of this paper. The decision on who would be inside the barrier protection and who would not is a major public policy issue that can be informed by the engineering community but the decision would be made by elected city, state or federal officials.

Continued Sea level Rise – Setting the design height will be strongly influenced by projections of future sea level rise. It has been argued that a barrier system would become obsolete since the barriers would be overtopped in the future by the higher storm surge caused by the rise in base water levels. While this is true, a barrier system would likely provide decades of protection from storm surges while allowing the region to develop and implement long term strategies to protect its infrastructure. These strategies could include building seawalls, raising street grids, rebuilding, reconfiguring and waterproofing critical utility and transit infrastructure, upgrading sewage treatment plants to reduce effluent entering the harbor, and instituting building codes that recognize the future base water levels. It is also important to understand that even an overtopped barrier provides protection, allowing only a portion of the storm surge to enter and raise water levels in the harbor.

Costs and Benefits - The capital cost of the Outer Harbor Gateway, spanning a 5 mile reach across the lower bay and including 13 miles of terrain enhancement (or berms), on either side was estimated in 2009 to be $5.9 billion (ASCE 2009). This barrier provides protection to heavily populated areas of New Jersey, Staten Island, Manhattan and portions of Queens, including JFK airport. This compares to the estimate for the 1 mile long Verrazano Narrow barrier of $6.5 billion (ASCE 2009), which protects a far smaller area from a storm surge. It is likely that the Outer Harbor Gateway would be used in conjunction with at least one other barrier, probably similar to the smaller East River Barrier presented at the 2009 ASCE conference, for which no construction cost estimate was provided.

The cost of building a barrier system should be viewed in light of the impacts that it is likely to prevent, and these can be difficult to qualify. The National Hurricane Center's Tropical Cyclone Report (Blake et al. 2012) summarizes Hurricane Sandy damage from a number of sources. These include damages of $400 million to the NJ Transit system, total damage to the entire transit, road and bridge system in New Jersey reaching $2.9 billion; damages in the city of Hoboken alone of $100 million; and total damage to New York City of $19 billion, inclusive of all private, public and indirect costs. Hurricane Sandy was preceded in 2011 by a near-miss from Hurricane Irene, which spurred a mandatory evacuation of 370,000 (NY Times) people and which caused estimated damages throughout the United States of around $15.8 billion (Masters, J.).

Both Hurricane Sandy and Hurricane Irene had reached Category 3 status before weakening as they approached the New York area coast. A paper by Hill (ASCE 2009) indicated that a Category 2 hurricane striking New York would cause damages of $200 billion, and argued that this was a modest amount in overall terms. The NYC Natural Hazard Mitigation Plan (2009) indicates that the annualized loss, or long-term average losses in a given year, is estimated as $276 million for total building structures. The same plan forecasts that, in a 50-year period, there is a 1 in 7 chance of a hurricane striking New York City, and a 1 in 30 chance of an intense hurricane (Category 3 or higher) hitting the New York City area. It also indicates that there is a 1 in 40 chance of a hurricane strike in any given season.

Information from the National Hurricane Center on hurricane tracks indicates that the estimated return period in years for Category 1 hurricanes passing within 50 nautical miles of New York is 19 years (National Hurricane Center), indicating that about three Category 1 hurricanes can be expected in a 50 year period. NOAA information (NWS TPC-5, 2007) records that there were 12 hurricane strikes on New York between 1851 and 2006, and 5 of these were Category 3.

The statistics of costs and potential impacts above are not easily compared. The damage estimates do not differentiate between areas that would have been protected by barriers and those that would not. A barrier system has not been well-defined, so the areas that may be protected are not yet clear. On the other hand, the damage estimates may well be understated since most tend to include only property damage and not ancillary damages such as lost productivity caused by damaged transportation and utility systems.

However, a simple order-of-magnitude comparison would indicate that a very favorable benefit to cost ratio could be realized by protecting highly valuable assets in New Jersey and New York with a system of barriers for the harbor. A similar simplistic comparison suggests that a barrier located between Sandy Hook and Rockaway would provide a higher rate of asset protection per dollar invested than barriers further from the ocean in deeper water.

ASSUMING IT GOES AHEAD

At this stage, the project has attracted considerable attention from city, state and federal authorities as well as the press and various other interested parties. In order to move forward, a number of actions will be required on various fronts. The regulatory system must be examined to identify required authorizations, certifications, public involvement, and waivers to obtain the necessary approvals for items such as planning and land acquisition. Pilot studies and engineering assessments, such as those described above, would be required to determine a preliminary project specification and to start a staged development of a workable solution. The Army Corps of Engineers will be a key player in undertaking technical evaluations and possibly design. Costs estimates of the developing solution will be required in order to initiate funding and budgetary applications and approvals. It is anticipated that this initial phase would take two years.

Once a concept has been finalized, the detailed design would be carried out. This would result in the preparation of drawings of the barrier, its components and equipment, together with materials and workmanship specifications for structural elements of the barrier and performance specifications for the MEICA components that could then be issued for bidding. It is anticipated that this design phase would take two years.

It is assumed that construction of the barrier and its commissioning would take six or seven years. Taken overall, and allowing for some overlapping of phases, it is suggested that a ten year schedule be considered at this stage.

It is possible that the above schedule could be accelerated. As an example, the Lake Borgne barrier, built as part of the system protecting New Orleans, was completed only seven years after Hurricane Katrina hit. This was accomplished by accelerating many of the steps described above, including critical federal approvals and funding.

REFERENCES

ACOE New York District Dredging Program, WEDA Eastern Chapter Annual Meeting, October 2012, http://operations.usace.army.mil/nav/12octWEDA/NAN_FY13-17DredgingPresentationFINAL.pdf

Blake, E.S., Kimberlain, T.B., Berg, R.J., Cangialosi, J.P., and Beven J. L., National Hurricane Center, Tropical Cyclone Report, Hurricane Sandy (AL182012) 22 – 29

October 2012, updated 12 February 2013, http://www.nhc.noaa.gov/data/tcr/AL182012_Sandy.pdf

Blake, E.S., Rappaport, E. N., Landsea, C.W., NOAA Technical Memorandum NWS TPC-5
The Deadliest, Costliest, and Most Intense United States Tropical Cyclones from 1851 to 2006 (and other frequently requested hurricane facts), updated 15 April 2007 for return period information http://www.nhc.noaa.gov/pdf/NWS-TPC-5.pdf

Bowman, M., Hill, D., Khinda, J.S., (2009). Proc., *Storm Surge Barriers to Protect New York City – Against the Deluge*, ASCE, Polytechnic Institute of New York University, Brooklyn, NY, 30-31 March 2009.

City of New York (March 2009), "*Natural Hazard Mitigation Plan*", http://www.nyc.gov/html/oem/html/about/planning_hazard_mitigation.shtml, retrieved 10 March 2013

Masters, J., "Hurricane Irene now rated 6th most damaging hurricane,"http://www.talkweather.com/forums/index.php?/topic/58197-dr-jeff-masters-hurricane-irene-of-2011-now-rated-historys-6th-most-damaging-hurricane/, May 3, 2012

National Hurricane Center, www.nhc.noaa.gov/climo/#returns

New York State Thruway Authority, Press Release, January 18, 2013; http://www.newnybridge.com/news/2013/2013-01-18-contract-approval.html

NOAA Nautical Chart 12327, April 2102

NY Times, *With Hurricane Irene Near, 370,000 in New York City Get Evacuation Order*, May 12, 2012, http://www.nytimes.com/2011/08/27/nyregion/new-york-city-begins-evacuations-before-hurricane.html?pagewanted=all&_r=0

Sustainable Infrastructure Guidelines, The Port Authority of NY&NJ, March 23, 2011

US Army Corps of Engineers Contract Drawings titled, "New York and New Jersey Harbor, Channel Navigation Improvement 50 ft Project, Ambrose Channels Contract. S-AM-3B, undated, https://www.fbo.gov/index?s=opportunity&mode=form&id=2f1352bf9695616e31bccc2769e25a23&tab=core&_cview=1.

US Army Corps of Engineers Navigation Data Center, U.S. Waterway Data, Vessel Entrances and Clearances, http://ndc.iwr.usace.army.mil/wcsc/webpub10/part1_wwys_tripsbydraft_cy2010.htm